

Interdisciplinary Research in Physics

Robert C. Spindel
Applied Physics Laboratory
University of Washington
1013 NE 40th Street
Seattle, WA 98105
phone (206)543-1310 fax (206)543-3521 email spindel@apl.washington.edu
Award Number N00014-96-1-0246
<http://www.apl.washington.edu>

OVERALL LONG-TERM GOAL

The express purpose given by the Chief of Naval Research for the creation of this program in 1979 was to promote collaborative research between APL and the various academic units of the University of Washington. Within this framework, our goal is to pursue high quality fundamental research which brings together APL staff and University faculty in new collaborations, ultimately leading to fuller participation of our staff in supervision of undergraduate, graduate student, and post doctoral research. A secondary goal is access to expertise and research facilities available outside APL for Navy-related research. The following four research projects were included in the FY 1998-1999 grant.

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Mathematical Aspects of Hamiltonian Theories for the Ocean

Frank S. Henyey (APL)

phone (206)543-4856 fax (206)543-6785 email frank@apl.washington.edu

C. Robin Graham (Mathematics)

OBJECTIVE

Our objective is to determine the usefulness of the Hamiltonian formalism for numerical modeling of ocean flow fields, including internal waves and turbulence, and to clarify the nature of conservation laws.

WORK COMPLETED and RESULTS

Two papers have been prepared for publication. The first is undergoing modification based on reviewer's comments, and the second is accepted.

The first paper compares two formulations of stratified fluid Hamiltonian theories. The two Hamiltonians are related by a canonical transformation, yet they have different gauge groups. Thousands of papers have been written about gauge groups, primarily about the physics of elementary particles, but this is the first time that it has ever been found that two different gauge groups describe equivalent dynamics. This result led to a deeper understanding of the conservation laws of density and potential vorticity for stratified fluids.

The second paper is concerned with the question of the existence of Hamiltonian representations. We found that, except in unusual cases, the standard Clebsch representation for a homogeneous fluid does not exist in any arbitrarily small region surrounding a point at which the vorticity vanishes. This is very surprising and claims to the contrary abound in the literature. On the other hand, the analogous representation for a stratified fluid does exist locally under generic conditions. As the Clebsch representation is a basic ingredient in many applications of the Hamiltonian method, this result may be useful in deciding appropriate regions of space in which to use the representation in various implementations.

A third paper will soon be written. We established that the stratified fluid representation exists globally in a simply-connected region (i.e., we assume no islands in the region being described) for flows which typically arise in practice. We believe that the result extends to the case of periodic boundary conditions in the horizontal, the case usually studied in numerical simulations; we are finishing the details of the proof. We will also try to find out the situation with an island present.

IMPACT/APPLICATIONS

Hamiltonians are also useful (although not as important) for linear systems. In particular, we are working on the Hamiltonian description of ocean acoustics. It is straightforward to make the narrow-angle parabolic approximation in the Hamiltonian context by simply dropping a term, but we have not

yet found out how to make the wide-angle parabolic approximation in a similar way. These results may be useful in handling the boundary conditions at the water-sediment interface.

Environmentally Adaptive Sonar Controller

Gregory M. Anderson (APL)

phone (206)543-4648 fax (206)543-6785 email gma@apl.washington.edu

Robert T. Miyamoto (APL)

Robert J. Marks II (EE)

Mohamed A. El-Sharkawi (EE)

LONG-TERM GOALS

The long term goal of this project is to build a ship sonar controller that will automatically tune onboard systems to maximize the performance of the sonar for undersea detection of threat submarines in the face of changing ocean environmental conditions.

OBJECTIVES

Our technical objective is to develop an adaptive controller that accepts high-level undersea surveillance objectives from an operator, and automatically computes adjustments to the ship's track and sonar control parameters to maximize the performance of the system in meeting the operators objectives.

APPROACH

Our approach is to develop a closed-loop, adaptive controller that operates in conjunction with ocean acoustic performance models and environmental assessment modules to compute the control adjustments. We are using a ray-based acoustic model (CASS/GRAB) for performance predictions, and plan to use the Sonar Environmental Parameter Estimation System (SEPES) to estimate bottom and surface conditions from the sonar measurements. We are working with the Department of Electrical Engineering to design two complimentary functions of the controller: 1) optimize the performance of the sonar in a particular environment, and 2) manage the ship's track to take advantage of environment conditions.

We are using computational intelligence techniques (e.g., neural networks, fuzzy controllers) to optimize sonar performance in a particular environment. We plan to use a multi-layered fuzzy controller to manage the subsystem controllers. One of the challenges the project faces is that the high-fidelity acoustic models required for accurate sonar performance modeling are slow, making it difficult to compute the sonar control adjustments in real time. We are using neural networks to quickly emulate the acoustic model calculations to overcome this problem.

We are exploring an iterative learning algorithm that uses clustering to organize a dynamic fuzzy rule base to accumulate control knowledge to compute the ship's track. The algorithm accepts high level tactical goals and performance estimates from the performance optimizer, and strives to meet surveillance goals supplied by the operator.

WORK COMPLETED

Last year we defined a closed-loop controller that addresses many of the important areas of wideband, variable depth sonar control. We divided the design into subcontrollers which address specific areas, including: 1) Doppler Processing, to switch between high and low doppler targets; 2) Ping Frequency and Bandwidth, to accommodate varying environmental noise levels and clutter response vs. frequency; 3) Ping Type, for selecting LFM, HFM, CW, and other pulse type considerations; 4) Signal Excess Optimizer, to select beam shape, tilt, and depth of the sonar; 5) Ping Schedule, to provide an mix of pings that accomplish high level tactical goals; and 6) Probability of Detection Area Control, to position the sonar pings (via the ship's track.) This year we focused our efforts on three of these areas: Signal Excess Optimization, Ping Frequency and Bandwidth, and Probability of Detection Area Control.

Signal Excess Optimizer

The Signal Excess Optimizer (SEO) subcontroller is based on experience gained using neural networks (NN) for electrical power grid security assessment and shorted electric motor rotor winding isolation. The SEO is designed to maximize search performance over a surveillance area by adjusting sonar control parameters. We have trained neural networks (NN) to emulate the calculations of the acoustic model across a range of expected environmental conditions. The NN accurately and very quickly emulates the acoustic model calculations to estimate the effect of sonar control parameter changes. Last year we used an range-independent acoustic model to train the NN. This year we switched to a higher fidelity, range-dependent model that can model variability in bottom depth, bottom slope, and a variety of surface, bottom and ocean volume conditions.

The NN inputs are the environmental parameters (e.g., wind speed, sound speed profile, bottom characteristics) and sonar control parameters (e.g., sensor depth). The output is signal excess as a function of range and depth. Several thousand acoustic model runs were used to train a multilayer perceptron NN. The resulting NN can accurately reproduce the model-computed detection map in less than a millisecond.

Originally we were using a narrow band pulse for our analysis, and could model the ocean response using a single NN. We inverted the NN directly to determine the sonar parameter settings that provide maximum signal excess, for a specific set of environmental conditions, and a surveillance area. We are now modeling a wideband transmit pulse using narrow subbands. The NN could be inverted for each subband, but that might lead to multiple solutions for a sonar control parameter because of frequency response variability of the ocean. We are currently looking at inversion approaches that will work for the wideband signals.

Ping Frequency and Bandwidth

Wideband active sonar systems provide enhanced down-range resolution, which leads to better signal-to-interference ratio for target detection by reducing reverberation levels. For some target/environment combinations, however, transmitting long linear or hyperbolic frequency modulated (LFM or HFM) signals and coherently processing over the entire band may not give the best possible performance. An algorithm named APLECORR (Adaptive PulseLength CORRection), developed by P. M. Baggenstoss

at NUWC/Newport, designs a wideband transmit pulse given information about ambient noise, reverberation, and target scattering spectra. This transmit pulse, when combined with a semicoherent receive processor, will optimize the detection index for the given scenario.

We are assessing the feasibility of using an algorithm like APLECORR into the overall controller structure. The published algorithm specifies reverberation and target spectra at a single range. We are investigating the design of a transmit pulse that is jointly optimized over a region of hypothesized target ranges and depths, as well as jointly optimized with other sonar control parameters (e.g., sonar depth).

Probability of Detection Area Control

Controlling the ship's position to improve probability of target detection over an area is being explored using a system referred to as the ORG. The ORG is an iterative software algorithm that models an artificial organism. It implements a flexible sensory interface for interfacing with a dynamic environment and an autonomous learning module that uses fuzzy clustering for memorizing stimuli and the ORG's reaction to them. The decision module uses the output from a long-term module and combines it with the output of reactive module to change the ORG's control functions. The ORG can provide an intuitive interface for adding heuristics for long-term objectives from human operators, and can improve its performance and learn changing environmental constraints by observing the effects of its actions on the environment.

RESULTS

Our results include the following:

- Trained NN's to emulate both range-independent and range-dependent models for a wide variety of environmental conditions.
- Inverted NN's (for narrowband signals) to calculate sonar control parameter values that maximize performance over a surveillance area.
- Connected NN's to a MATLAB graphical user interface so the sonar performance can be quickly examined for a range of environmental conditions.
- Implemented an algorithm (APLECORR) to design an optimal pulse based on ambient noise, reverberation levels, and expected target strength. The algorithm constructs a pulse from subpulses by optimizing subpulse time, frequency, and bandwidth.
- Demonstrated feasibility of the ORG, an iterative learning program used to compute ship search patterns.

IMPACT/APPLICATIONS

If successful, the approach we are taking will help automate the activities of several ship sonar operators, and will help realize the Navy's reduced ship staffing goals for the 21st century.

TRANSITIONS

We used this work as a basis for response to a Broad Agency Announcement DD21 Phase 1 Solicitation, and we are continuing work under a PEO/USW project entitled “Environmental Adaptation Enhancements to LBVDS.”

RELATED PROJECTS

The controller relies on up-to-date knowledge of environmental conditions. The project is therefore related to the Sonar Environmental Parameter Estimation System (SEPES, under development at APL-UW) which extracts key acoustic model inputs (bottom loss, bottom backscatter, surface loss, surface backscatter) from sonar reverberation measurements.

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Influence of Local Variations in Surficial Sediment Porosity on the Spatial Distribution of Bacterial Numbers and Activity

Dajun Tang (APL)

phone (206)543-1290 fax (206)543-6785 email djtang@apl.washington.edu

Kevin Williams (APL)

Peter Jumars (School of Oceanography)

LONG-TERM GOALS

To obtain the spatial heterogeneity of sediment porosity on the centimeter scale in order to interpret high frequency bottom backscatter acoustic data and to access the impacts of biological activities on the variation of sediment heterogeneity.

OBJECTIVES

To build a multi-sensor conductivity probe system mounted on a bottom-mounted, self-contained frame. The system can take sediment conductivity measurements over a volume that is 100 cm long, 15 cm wide, and 15 cm deep. The spatial resolution of the measurements will be 1 cm in the horizontal dimensions and as small as 0.1 cm on the depth dimension.

APPROACH

The conductivity probe is built based on a technology already tested by Tang two years ago. The key element of the design is to construct electrodes, which have sub-millimeter diameters. A major part of the project is to build a frame which holds the conductivity probes. In order to take data on fine spatial grids, a horizontal and a vertical drive are designed and mounted to the frame. The completed system will allow the conductivity probes move in two dimensions and take data at centimeter grid points.

WORK COMPLETED

The system described above has been completed and tested at the APL-UW dock in September 1999 as well as in laboratory settings. The mechanical performance of the system is satisfactory. Analysis of data collected from these trials proved that the system meets the requirements in the proposal. The personnel contributed substantially to the project are Mike Welch (mechanical engineering), Harold Kolve (electrical engineering), and John Elliott (software engineering).

RESULTS

The conductivity system was successfully deployed in the ONR high-frequency bottom DRI experiment in Panama City, Florida, in October, 1999. In situ data of sediment roughness and sub-bottom heterogeneity were obtained. These data sets are first of their kinds and will have an immediate impact on interpreting the acoustics data also collected in the same area during the DRI experiment.

IMPACT/APPLICATIONS

Preliminary analysis of the conductivity data shows that the sandy sediment in the DRI site has a rough topography that obeys a power-law spectrum with an exponent of 2. Using such a spectrum as input to models of sound penetration into sediment by Darrell Jackson, the model/data comparison has shown great consistency. The volume heterogeneity spectra will be estimated in the next few months using the data from the conductivity system and further application of the results can be expected when the DRI acoustics data analysis are performed. The application of the data in interpreting sediment biological activities will also be extensively studied in the next few months.

TRANSITIONS

This system will be available for use by the underwater acoustics community and the sediment biology community. Potentials of applying the system to other oceanographic studies are yet to be fully explored.

RELATED PROJECTS

This instrument is closely related to the ONR high-frequency DRI. It provides the DRI project with unique ground-truth data of the sediments.

Response of Gas-Filled Bubbles to an Ultrasound Beam

Peter P. Chang (APL)

phone (206)543-1324 fax (206)543-6785 email pchange@apl.washington.edu

Steve Kargl (APL)

Udo Schmiedl (Radiology)

LONG-TERM GOALS

The long-term goal of this project is to obtain, through experimental measurements, the fundamental physical and acoustical properties of stabilized gas-filled microbubbles (ultrasound contrast agents).

OBJECTIVES

The objectives of the project are (1) to determine the acoustic parameters that affect the dynamical response of the microbubbles (amplitude, frequency, pulse length, pulse repetition frequency), (2) to measure the amplitude thresholds at which these microbubbles undergo inertial cavitation, and (3) correlate the type of bubble response with the amount of microbubble induced bioeffect.

APPROACH

An experimental arrangement consisting of a diagnostic transducer (5 MHz) and a therapeutic transducer (1.1 MHz) has been developed to accomplish the objectives (1) and (2). We are currently developing a method to accomplish objective (3), which is a work that goes beyond that originally proposed. We will use the information obtained from objectives (1) and (2) to determine the mechanisms responsible for ultrasound accelerated hemolysis and thrombolysis.

WORK COMPLETED

Objectives (1) and (2) have been completed. The contrast agent investigated was Albunex™.

RESULTS

We have identified two pressure thresholds at which Albunex™ microbubbles undergo inertial cavitation (here, defined as the collapse of gas bubbles followed by emission of an acoustic broadband noise). The first threshold (P1) corresponds to the pressure at which all the microbubbles in a cavitation field lose their property as an effective scatterer, because of fragmentation or deflation. The second threshold (P2) is associated with the acoustic reactivation of the remnants of the contrast agents and is related to the onset of more violent inertial cavitation. P1 and P2 were measured as a function of Albunex™ concentration, pulse length, and pulse repetition frequency.

IMPACT/APPLICATIONS

The results of this investigation have potential significance for both diagnostic and therapeutic ultrasound applications. They would: (1) permit improvement of existing contrast-based ultrasonic

imaging, (2) provide a means for development of drug-encapsulated microbubbles that can be “programmed” for fragility, thus permitting targeted delivery of chemicals to tissues via externally applied ultrasound, and (3) facilitate cavitation-related mechanical bioeffects.

TRANSITIONS/RELATED PROJECTS

Our results have generated three research proposals in collaboration with three private companies. Each company will be able to address in more detail the three applications described above (in the order listed). The proposals submitted and approved are the following:

- 1) “The physics of ultrasound contrast agents,” \$1.0M, RO-1 proposal submitted to the NIH, in collaboration with ATL Ultrasound.
- 2) “Investigation of a third generation echo-contrast agent,” \$127K, starting in Nov 99 (STTR - Phase I), in collaboration with Point Biomedical Corp.
- 3) “Characterization of gas carrier agents exposed to therapeutic ultrasound,” \$70K, Washington Technology Center (7/99 – 5/00), in collaboration with Ekos Corporation.

PUBLICATIONS

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- 5) P.P. Chang, “Optimal acoustic parameters for ultrasound contrast imaging,” 2nd International Ultrasound and Magnetic Resonance Conference in Vascular Disease, Seattle, Oct. 1998.